

Search for the standard model Higgs boson decaying to a $b\bar{b}$ pair in events with no charged leptons and large missing transverse energy using the full CDF data set

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We report on a search for the standard model Higgs boson produced in association with a vector boson in the full data set of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF II detector at the Tevatron, corresponding to an integrated luminosity of 9.45 fb^{-1} . We consider events having no identified charged lepton, a transverse energy imbalance, and two or three jets, of which at least one is consistent with originating from the decay of a b quark. We place 95% credibility level upper limits on the production cross section times standard model branching fraction for several mass hypotheses between 90 and 150 GeV/c^2 . For a Higgs boson mass of $125 \text{ GeV}/c^2$, the observed (expected) limit is 6.7 (3.6) times the standard model prediction.

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In the standard model (SM) [1], the mechanism responsible for spontaneous electroweak symmetry breaking gives mass to the W and Z bosons [2]. The Higgs boson (H) represents the remaining degree of freedom after the symmetry is broken and also allows fermions to acquire mass through Yukawa couplings. Although there is strong evidence of electroweak symmetry breaking, the Higgs boson has yet to be observed. The SM does not predict the mass of the Higgs boson, m_H , but the combination of precision electroweak measurements [3], including recent top quark and W boson mass measurements from the Tevatron [4, 5], constrains $m_H < 152 \text{ GeV}/c^2$ at the 95% confidence level. Direct searches at LEP2 [6], the Tevatron [7], and the LHC [8] exclude all possible masses of the SM Higgs boson at the 95% confidence level or the 95% credibility level (C.L.), except within the ranges $116.6 - 119.4 \text{ GeV}/c^2$ and $122.1 - 127 \text{ GeV}/c^2$.

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A SM Higgs boson in this mass range would be produced in the $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions of the Tevatron, and would have a branching fraction to $b\bar{b}$ greater than 50% [9–11]. In these currently allowed regions, $H \rightarrow b\bar{b}$ is the dominant decay mode, but large QCD multi-jet backgrounds overwhelm searches in the exclusive $b\bar{b}$ final state. Searches for H produced in association with a vector boson, VH ($V = W$ or Z), where the vector boson decays leptonically, access final states with significantly higher signal to background ratios than those resulting from $gg \rightarrow H \rightarrow b\bar{b}$.

This Letter presents a search for VH production in events with missing transverse energy (\cancel{E}_T) [12] – a signature of neutrinos escaping detection – and b jets in a data set corresponding to an integrated luminosity of 9.45 fb^{-1} collected using the CDF II detector at the Fermilab Tevatron. This analysis considers $Z(\rightarrow \nu\bar{\nu})H$ production, where the neutrinos (ν) escape detection, or $Z(\rightarrow \ell^+\ell^-)H$ when neither charged lepton is identified or they are reconstructed as jets. We are also sensitive to WH events where $W \rightarrow e\nu$ or $W \rightarrow \tau\nu$ and the charged lepton is reconstructed as a jet, or where it is not identified. By building upon techniques used for the observation of single-top-quark production [13], we significantly increase the signal acceptance with respect to previous Tevatron searches in this final state [14, 15].

CDF II is a multi-purpose collider detector described in Ref. [16]. A three-level online selection system (trigger) is used to select events for analysis. Events are selected via boolean OR of two trigger paths [17] requiring either the presence of large \cancel{E}_T , or large \cancel{E}_T and two jets [18]. The efficiency associated to this selection is obtained from data and is applied to the Monte-Carlo (MC) simulated samples to reproduce the inefficiencies present in the data. The parametrization of the trigger efficiency [19] significantly improves the modeling of the trigger turn-on outside the fully efficient region, as verified using data control samples. This allows significantly relaxed pre-selection requirements compared to that of Ref. [14]. The parametrization is done using a neural network (NN) [20] trained from the following inputs: the \cancel{E}_T in the event, its azimuth ($\varphi(\vec{\cancel{E}}_T)$), three variables characterizing the i th jet (j_i) in the event – $E_T(j_i)$, $\eta(j_i)$ and $\varphi(j_i)$ – and the η - ϕ separation of the jets $\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$ [12]. We thus have 9 (14) input variables for events with two (three) jets. We use a muon-triggered sample to define the nominal parametrization and derive the trigger systematic uncertainty from a parametrization of an inclusive jet sample with at least one jet with $E_T > 50$ GeV.

We reconstruct jets from energy depositions in the calorimeter towers using a jet clustering cone algorithm [18] with a cone of radius $\Delta R = 0.4$. In addition to the standard jet-energy corrections used by CDF [18], we adjust the energy of the jets according to the measured momentum of the charged particle tracks within the jet cone [21]. We further improve the energy deter-

mination using a NN approach to estimate the energies of the initiating quarks. The direction and magnitude of the $\vec{\cancel{E}}_T$ are then recomputed. These jet reconstruction methods improve both the signal acceptance and the relative resolution of the reconstructed invariant mass of the Higgs boson candidate by $\sim 15\%$. We reject events with an identified e or μ to maintain statistical independence from other CDF analyses searching for the SM Higgs boson [22, 23].

After the events are reconstructed, the following pre-selection requirements are made: we select events with $\cancel{E}_T > 35$ GeV and two or three jets satisfying $E_T > 15$ GeV and $|\eta| < 2.4$, thus accepting events where partons provide an additional jet candidate, or a lepton (e or τ) is reconstructed as a jet. The two most energetic jets, j_1 and j_2 , are required to have reconstructed transverse energies of at least 25 and 20 GeV respectively, satisfy $|\eta(j_i)| < 2$, be separated by $\Delta R(j_1, j_2) > 0.8$, and at least one of these two jets must satisfy $|\eta(j_i)| < 0.9$. This selection is relaxed with respect to Ref. [14], and increases the signal acceptance by a factor of 1.4. The cost of this increased signal acceptance is a tenfold increase of the background acceptance. One of the leading sources of significant \cancel{E}_T in QCD (quantum chromodynamics) production of multi-jet events (QCD MJ) arises from the mismeasurement of jet energies. Neutrinos from semileptonic b decays can also produce significant \cancel{E}_T in QCD MJ events. In both of those cases, the $\vec{\cancel{E}}_T$ is often aligned with $\vec{E}_T^{j_2}$, and such events are rejected by requiring $\Delta\varphi(\vec{\cancel{E}}_T, \vec{E}_T^{j_1}) \geq 1.5$ and $\Delta\varphi(\vec{\cancel{E}}_T, \vec{E}_T^{j_2}) \geq 0.4$. This reduces the backgrounds by a factor of three, while retaining 90% of the signal. The large backgrounds from light-flavor jet production originating from u , d , or s quarks or gluons are reduced by identifying (tagging) jets consistent with the decay of b quarks.

We use two algorithms to tag b -quark jets, SECVTX [24], which attempts to reconstruct the secondary vertex from the b decay (displaced from the interaction point because hadrons containing b or c quarks can travel a few millimeters in the detector before decaying), and JETPROB [25], which determines for each jet the probability that the tracks within the jet are consistent with originating from the primary vertex. We operate SECVTX (JETPROB) at about 40% (50%) efficiency, yielding a rate of light-flavor jets mistakenly identified as b jets (mistags) of about 1% (5%). We exploit the different purities of the selected multi-tagged events by considering independent tagging categories separately and later combining results. We require that one of the leading jets be tagged by SECVTX and the other be tagged either by SECVTX (SS) or JETPROB (SJ), or be untagged (1S). The tagging process reduces the backgrounds by two orders of magnitude while retaining about 50% of the signal. Events satisfying the aforementioned criteria comprise the *preselection* sample. The signal-to-background ratio (S/B) in this sample is esti-

mated to be $S/B \sim 1/400$ in the SS tagging category for $m_H = 115 \text{ GeV}/c^2$, compared to less than 10^{-5} for the full sample of triggered events. The relative fraction of events with $Z \rightarrow \nu\bar{\nu}$, $Z \rightarrow \ell^+\ell^-$, and $W \rightarrow \ell\nu$ is respectively 47, 3 and 50 percent; of the latter, the fraction with electron (e), muon (μ), and tau (τ) decays is respectively 30, 20 and 50 percent.

Backgrounds from top-quark events via pair and electroweak production (top), V +jets events, and diboson events (VV) are all modeled via simulation. The ALPGEN generator [26] is used to estimate V +jets, POWHEG [27] for electroweak production of top quarks, and PYTHIA [28] for top quark pair production and VV events, as well as for the VH signal. The parton showering is performed by PYTHIA. The event generation process includes a simulation of the detector response [29], and the resulting samples are subjected to the same reconstruction and analysis chain as the data. The normalization of the simulated samples is described in Ref. [7]. Electroweak (EWK) mistags, events with light-flavor jets that are wrongly tagged, are mostly due to V +jets and are determined from light-flavor simulated samples weighted by a per-event mistag probability, obtained for each algorithm from an orthogonal data sample [24, 25].

The background contribution from QCD MJ events is difficult to describe accurately with the simulation, and so is modeled separately from an independent data sample. We predict the QCD MJ contribution from data events with $\Delta\varphi(\vec{E}_T, \vec{E}_T^{j_2}) < 0.4$ and $35 < \cancel{E}_T < 70 \text{ GeV}/c^2$. We measure in this sample the contamination from events with heavy-flavor jets or light-flavor mistags fall into one of the three previously described tagging categories [19].

Following Ref. [14], we parametrize this category-tagging rate in bins of the magnitude of the negative vector sum of the transverse momenta of the charged tracks within the jet (\vec{p}_T^{tr}) [30], the scalar sum of transverse energies of j_1 , j_2 , and j_3 (where applicable) H_T , $Z[j_1]$, and $Z[j_2]$, where $Z[j] \equiv \sum p_T^{\text{tr},j}/p_T^j$; this defines one matrix (M_{TR}) for each tagging category. The large data sample available allows improvement of this model by defining an *event-based* M_{TR} instead of a *jet-based* M_{TR} . The advantage is that correlations between the jets in each event are properly taken into account. We use the M_{TR} to predict the QCD MJ contribution in the preselection, which has the same flavor composition before tagging requirements as in the region from which the M_{TR} is derived. The QCD MJ background normalization in each tagging category is determined from the corresponding M_{TR} after subtracting the contributions from all other background sources, which are estimated using simulated events. The model is validated in various control regions, defined below.

We employ an artificial neural network, NN_{QCD} , to further separate the dominant QCD MJ background

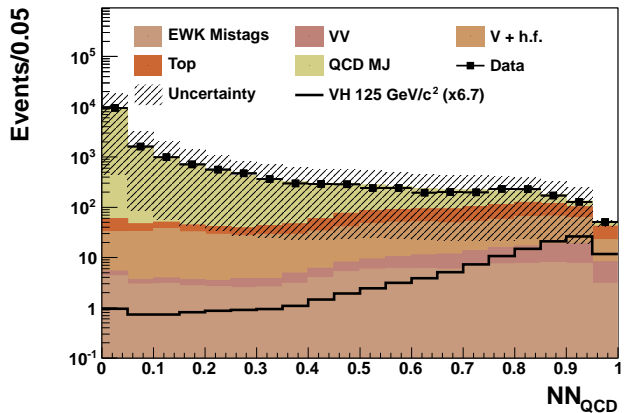


FIG. 1: The distribution of NN_{QCD} for events satisfying the preselection criteria. The signal region is defined by $\text{NN}_{\text{QCD}} > 0.45$. The normalization of the QCD MJ contribution is determined from the data.

from the signal and other backgrounds. We train a 14-variable feed-forward multilayer perceptron bearing energy-derived (\cancel{E}_T , p_T^{tr}), angular ($\Delta\varphi(\vec{E}_T, \vec{p}_T^{\text{tr}}$), angular separations between \vec{E}_T , \vec{p}_T^{tr} and the jet directions), and event shape (centrality and sphericity) observables [19]. Figure 1 shows the distribution of NN_{QCD} in the preselection sample; the QCD MJ backgrounds (peaking at 0) are clearly separated from the signal (peaking at 1). We retain only events with $\text{NN}_{\text{QCD}} > 0.45$ (signal region), rejecting about 90% (70%) of the QCD MJ (overall) background while keeping 95% of the signal. This represents a 15% increase in background rejection for the same signal acceptance compared to Ref. [14]. The S/B in the signal region is about $1/60$ in the SS tagging category for $m_H = 125 \text{ GeV}/c^2$, similar to that of the corresponding tagging category of Ref. [31].

We employ a second network, NN_{SIG} , to discriminate

TABLE I: Comparison of the number of expected and observed events in the signal region for different tagging categories. The uncertainties include statistical and systematic contributions.

Process	2 b tags	1 b tag
	SS + SJ	1S
VV	62 ± 7.5	293 ± 32
Top	370 ± 52	1015 ± 128
V + heavy flavor	424 ± 81	3680 ± 675
EWK mistags	55 ± 26	2288 ± 283
QCD MJ	1300 ± 31	10825 ± 177
Total	2211 ± 197	18100 ± 1295
Data	2117	18165
Expected Higgs boson signal for $m_H = 125 \text{ GeV}/c^2$		
$ZH \rightarrow \nu\nu b\bar{b}$	7.6	9.7
$WH \rightarrow \ell\nu b\bar{b}$	8.0	10.6
$ZH \rightarrow \ell\ell b\bar{b}$	0.4	0.6

the expected signal from the remaining backgrounds. Seven input variables are used for this purpose: the invariant mass of the two leading jets ($m(j_1, j_2)$), the invariant mass of \cancel{E}_T and all jets, the differences $H_T - \cancel{E}_T$ and $\cancel{H}_T - \cancel{E}_T$ (\cancel{H}_T is the magnitude of the negative vector sum of jet E_T 's), the maximum ΔR between the jets, the output of NN_{QCD} , and the output of a NN using tracking information to separate events with intrinsic \cancel{E}_T from those with instrumental \cancel{E}_T [32].

We avoid potential bias by testing our understanding of the SM backgrounds in several control samples where the expected amount of signal is negligible. We define an EWK region (Fig. 2(a)) by requiring events to have at least one charged lepton in addition to satisfying the preselection criteria. This region is sensitive to top-quark pair, V +jets, and, to a lesser extent, VV and electroweak single-top-quark production, and is used to validate the simulation against the data. We also define the MJ1, MJ2, and MJ3 control regions, which contain no identified lepton and are dominated by QCD processes. MJ1 (Fig. 2(b)) contains events with $\Delta\varphi(\vec{\cancel{E}}_T, \vec{E}_T^{j_2}) < 0.4$ and $\cancel{E}_T > 70$ GeV. MJ2 contains events satisfying the preselection requirements and $\text{NN}_{\text{QCD}} < 0.1$ and is the region where the QCD MJ normalization is obtained from the data. MJ3, defined from preselection events with $0.1 \leq \text{NN}_{\text{QCD}} \leq 0.45$, serves as a final consistency check of the overall normalization. Finally, we validate our background model in the preselection region before proceeding with the final fit in the signal region. We check the distribution of multiple kinematic variables, including all inputs to NN_{QCD} and to the final discriminant function NN_{SIG} , defined in the next paragraph, as well as the output of these two networks in all our control samples [19]. We obtain good agreement between the data and our SM background model in all the samples, with only the normalization of the QCD MJ component determined from the fit to data.

The distribution of NN_{SIG} is validated in our control samples, as shown in Fig. 2 for events with two b tags. Figure 2(c) shows the distribution of NN_{SIG} in the signal region for events with two b tags. The expected number of events is compared to the observed yields in Table I. For $m_H = 125$ GeV/ c^2 , we expect a total of 21 (16) signal events with one (two) b -tagged jets.

We perform a binned likelihood fit to probe for a VH signal in the presence of SM backgrounds. The likelihood is the product of Poisson probabilities over the bins in the NN_{SIG} distribution. The mean number of expected events in each bin includes contributions from each background source and from the VH processes (assuming a given value of m_H). We employ a Bayesian likelihood method [33] with a flat, non-negative, prior probability for the SM Higgs boson production cross section times branching fraction, $\sigma(VH) \times \mathcal{B}(H \rightarrow b\bar{b})$, and truncated Gaussian priors for the uncertainties on the acceptance and shape of the backgrounds. We combine the three tag-

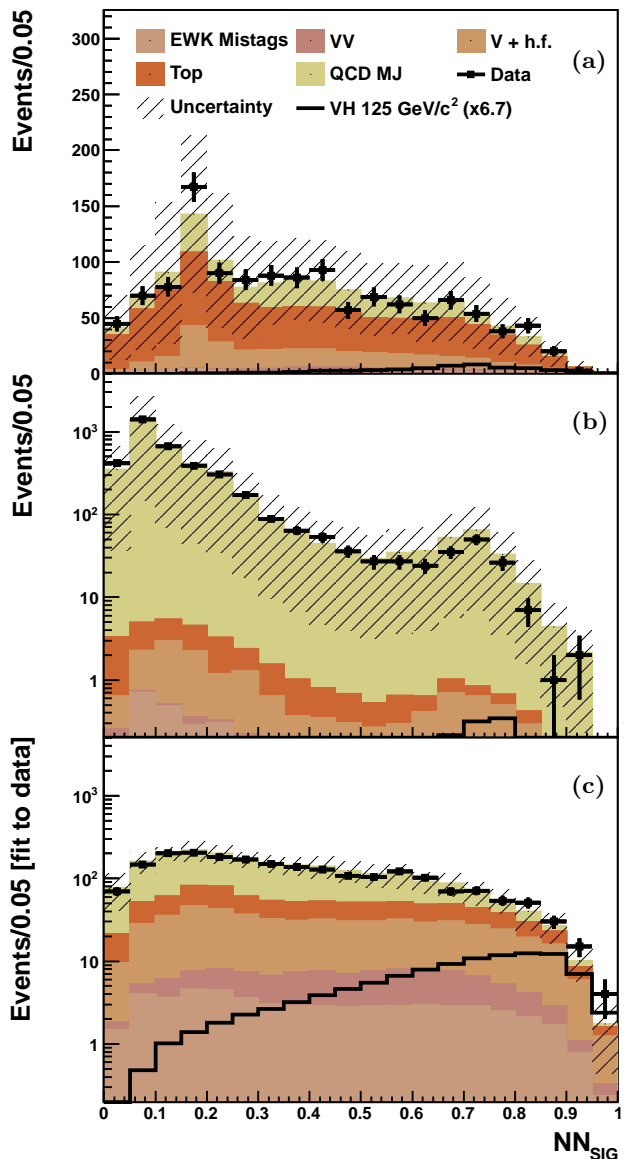


FIG. 2: The distribution of the final discriminant function, NN_{SIG} , for events with two b tags (SS+SJ categories) in the control samples: (a) EWK, (b) MJ1, (c) signal region ($\text{NN}_{\text{QCD}} > 0.45$). Only the normalization of the QCD MJ is fit to the data.

ging categories by taking the product of their likelihoods and simultaneously varying the correlated uncertainties. All systematic uncertainties except those associated with the QCD MJ and the EWK mistags are treated as fully correlated across the tagging categories.

The uncertainties from the simulations statistics and those on the normalizations of top-quark (10%), diboson (6%), V +jets (30%), QCD MJ (1 to 3%), and EWK mistags (20 to 65%) production are not correlated. The shapes obtained by varying the M_{TR} (mistag) probabil-

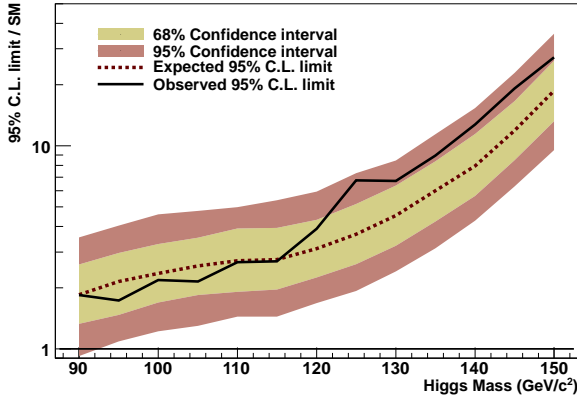


FIG. 3: Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on VH cross section times $\mathcal{B}(H \rightarrow b\bar{b})$ divided by the SM prediction, as a function of the Higgs boson mass. The bands indicate the 68% and 95% credibility regions where the limits can fluctuate, in the absence of signal.

ities by one standard deviation from their central values are applied as shape uncertainties for the QCD MJ (EWK mistags). The correlated uncertainties, which apply to both the signal and the EWK backgrounds, include luminosity measurement (6%), b -tagging efficiency (5 to 10%), trigger efficiency (3-5%), lepton veto efficiency (2%), parton distribution function (3%), and up to 11% for the jet-energy scale [18]. We assign shape uncertainties on NN_{SIG} due to the jet-energy scale and the trigger efficiency. The latter two also affect the QCD MJ background through the background subtraction procedure described above. Initial- and final-state radiation uncertainties (2 to 3%) are applied only to the VH signal.

Observing no significant excess in the data, we compute 95% C.L. upper limits on $\sigma(VH) \times \mathcal{B}(H \rightarrow b\bar{b})$ for $90 < m_H < 150 \text{ GeV}/c^2$ in $5 \text{ GeV}/c^2$ steps using the methodology described in Ref. [34]. The expected and observed upper limits are shown in Table II. The observed limits are compatible with the expectations calculated assuming no VH signal is present in the data.

In summary, we have performed a direct search for the SM Higgs boson decaying into $b\bar{b}$ pairs using the full CDF II data sample, corresponding to 9.45 fb^{-1} of integrated luminosity accumulated during Run II of the Tevatron. Improved techniques increase the sensitivity by roughly 15% with respect to a previous analysis [14] in addition to the improvement due to larger integrated luminosity. We observe no significant data excess over SM backgrounds and set 95% C.L. upper limits on $\sigma(VH) \times \mathcal{B}(H \rightarrow b\bar{b})$ for $90 < m_H < 150 \text{ GeV}/c^2$ with $5 \text{ GeV}/c^2$ increments. For a Higgs boson mass of $125 \text{ GeV}/c^2$, the observed limit is 6.7 times the SM prediction, consistent with the expected limit of 3.6 within two standard deviations.

TABLE II: Expected and observed 95% C.L. upper limits on the VH cross section times $\mathcal{B}(H \rightarrow b\bar{b})$ and their ratio to the SM prediction [7].

m_H (GeV/ c^2)	$\sigma_{VH} \times \mathcal{B}(H \rightarrow b\bar{b})$ (pb)		Ratio to SM prediction	
	Expected	Observed	Expected	Observed
90	$0.92^{+0.40}_{-0.27}$	0.92	$1.8^{+0.8}_{-0.5}$	1.8
95	$0.91^{+0.34}_{-0.29}$	0.73	$2.2^{+0.8}_{-0.7}$	1.7
100	$0.82^{+0.33}_{-0.24}$	0.77	$2.3^{+0.9}_{-0.7}$	2.2
105	$0.75^{+0.30}_{-0.21}$	0.63	$2.6^{+1.0}_{-0.7}$	2.1
110	$0.65^{+0.28}_{-0.19}$	0.64	$2.7^{+1.2}_{-0.8}$	2.8
115	$0.54^{+0.23}_{-0.16}$	0.53	$2.7^{+1.2}_{-0.8}$	2.7
120	$0.49^{+0.20}_{-0.13}$	0.61	$3.1^{+1.3}_{-0.9}$	3.9
125	$0.44^{+0.17}_{-0.12}$	0.81	$3.6^{+1.4}_{-1.0}$	6.7
130	$0.41^{+0.17}_{-0.12}$	0.60	$4.6^{+1.9}_{-1.4}$	6.7
135	$0.38^{+0.16}_{-0.11}$	0.57	$6.0^{+2.5}_{-1.8}$	8.9
140	$0.34^{+0.15}_{-0.10}$	0.55	$8.0^{+3.4}_{-2.3}$	12.7
145	$0.33^{+0.13}_{-0.09}$	0.53	$11.8^{+4.8}_{-3.4}$	19.2
150	$0.30^{+0.13}_{-0.09}$	0.45	$18.4^{+7.6}_{-5.2}$	27.2

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